branch to create a bias for transistor-3. And then of course, we do have the below transistor and then we do have the Q_2. This is Q_1, this is Q_3, this is Q_4 and then we do have the reference current here. And of course, we do have the application circuit, it is here.

Now, this is this is I should say more practical circuit. Now if I compare the 2 circuits, definitely I am getting higher resistance in this case. But the only drawback here it is the minimum required voltage to get this benefit it is higher namely, for this case we require one V_{CE} or rather $V_{CE(sat)}$.

So, minimum required voltage = $V_{CE(sat)}$ here or transistor-3 plus this voltage. And in fact, that voltage if I go through this loop, it can be shown that this voltage and this voltage they are equal. So, that is one $V_{BE(on)}$. Whereas for this simple current mirror, the minimum required voltage here it was only $V_{CE(sat)}$. So, that is the only you know limitation. So, we do have a requirement here it is $V_{CE(sat)} + V_{BE(on)}$.

Whereas, for the other circuit for this circuit we require only $V_{CE(sat)}$, $V_{CE(sat)}$ of transistor-2. So, that is how we can increase the output resistance and we can get the less dependency of the output current on the output voltage.

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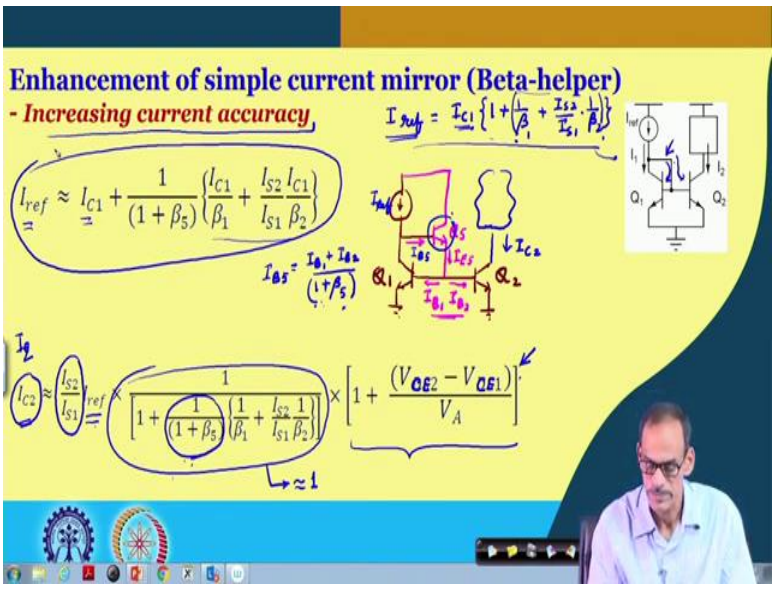

So the other factor, other non-ideality factor, namely, dependency on β you may recall that in the expression of the final current, particularly, for the BJT based circuit there are

some loss of the reference current because, it is supplying the I_B here and I_B here and the relationship of I_{ref} with I_{C1}, it was $I_{ref} = I_{C1}\left\{1 + \frac{1}{\beta_1} + \frac{I_{S2}}{I_{S1}} \cdot \frac{1}{\beta_2}\right\}$. This is the case for the simple current mirror.

Now, to avoid this loss or to reduce this loss, what we can do? We can place one transistor here, we can place one transistor here, which may work as current amplifier which is referred as Beta-helper circuit. So, the circuit is like this. We do have the reference current then we do have lower one, the Q_1 and also the Q_2.

Similar to the previous case Q_1 and Q_2, but in addition to that, we do have one extra transistor which is increasing this current here. So, if the base current here it is say, I_{B1} and this is I_{B2} which is emitter current of this transistor. So, let me call this is transistor-5 and I_E of transistor-5, it is summation of this 2 current.

So, the current at the base of this transistor it is ah, I can say this is I_{B5}. And $I_{B5} = \frac{I_{B1}+I_{B2}}{1+\beta_5}$. So, we can say that by adding this extra transistor, the loss of this current loss of this reference current; if I say that is the loss, then that is getting reduced by this factor. As a result, the relationship between I_{ref} and I_{C1}, instead of this equation, in this part, you will get a factor which is $(1 + \beta_5)$.

So, this is the corresponding relationship. $I_{ref} = I_{C1}$ multiplied by this factor and then this part. So, what is its consequence? The final expression of this I_2 or I_{C2}, if I say this is the I_{C2} and then we do have the application circuit here. And so, it is having $\frac{I_{S2}}{I_{S1}} \times I_{ref}$ and then this factor, we can see it is getting improvised by adding this $(1 + \beta_5)$. And this part however, it is remaining as is once again, sorry, this would be $V_{CE2} - V_{CE1}$.

So this part, we already have discussed to improve this one we can put the cascode structure. In addition, we can put this transistor to make this non-ideality factor very very close to 1. So, this is referred as Beta-helper circuit by the β of this transistor we are making this factor more towards the ideal one. So, that is why it is referred as Beta-helper circuit.

So, that is the expression of the final current, whatever you see, I_O or I_2. I think these are the two possible way of improving the circuit and by doing this, as I said that non-

ideality factor it is going close to 1. In other words, Beta-helper circuit it increases the accuracy of the current.

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Now to summarize, what are the things we have discussed in this lecture, we have started with motivation of going for current mirror namely, to implement current biasing element in amplifier, we require the current mirror. And we also have discussed about basic characteristic namely, output impedance of the current bias element or current biasing element should be as high as possible.

And in addition to that, the current mirror also works as signal mirroring circuit. Later, we will be talking about how it is really doing that. But just to give a hint, that it also has good application in current mode amplifier to mirrored signal; not only mirroring signal, it also helps to amplify current mode signal.

Then we have talked about the basic structure of current mirror and to get the basic structure, we have discussed about various versions of current biasing elements, namely simply registered and then leading to active device, and then we are we have discussed about the final version which is current mirror.

And the structurally, current mirror it is having a current reference followed by a mirror pair transistor. And then after the break, we have discussed more detail about the expression of the output current. So, we have gone through detailed circuit analysis and

we have derived the expression of output current of a current mirror in terms of reference current, and then aspect ratio or the reverse saturation current ratio.

Then we also have talked about the output resistance and then finally, we have talked about advancement of current mirror namely, cascode current mirror and also, so, this is for both BJT and MOS and then also we have talked about Beta-helper. So, Beta-helper, it improves the non-ideality factor. Second, non-ideality factor of BJT current mirror due to whatever the loss it was having in the base bias.

So, I think that is all we have discussed, we yet to discuss 1 more item small-signal model of current mirror. That it will be discussed in the next lecture along with other topic.

Thank you for listening.